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Interactive manipulation of microparticles in an octagonal sonotweezer

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An ultrasonic device for micro-patterning and precision manipulation of micrometre-scale particles is demonstrated. The device is formed using eight piezoelectric transducers shaped into an octagonal cavity. By exciting combinations of transducers simultaneously, with a controlled phase delay between them, different acoustic landscapes can be created, patterning micro-particles into lines, squares, and more complex shapes. When operated with all eight transducers the device can, with appropriate phase control, manipulate the two dimensional acoustic pressure gradient; it thus has the ability to position and translate a single tweezing zone to different locations on a surface in a precise and programmable manner. © *2013 AIP Publishing LLC* [http://dx.doi.org/10.1063/1.4802754]

Techniques that allow the manipulation of cells and micro-particles by non-invasive means are desired to facilitate biological applications such as microarrays[1] and tissue engineering.[2] Non-invasive techniques exploiting the acoustic radiation force have been demonstrated for trapping,[3,4] separating,[5,6] and rotating particles.[7]

Devices with four or fewer transducers that generate counter-propagating surface[8,9] or bulk[10] acoustic waves have been used to demonstrate patterning and displacement of micro-particles. However, due to the low number of degrees of freedom, pattern shapes and displacement are limited. Trapping, patterning, and displacement of microspheres and cells has also been demonstrated in a heptagonal sonotweezer.[11,12] In these devices, streaming effects due to the asymmetry of the manipulation chamber and the transducers were generated.

In this letter, an octagonal array of elements surrounding a fluid filled chamber is used to trap, pattern, and displace micro-particles. The octagonal device that is presented allows various patterns to be formed from the interference of travelling waves including lines, squares, or more complex shapes by exciting two, four, six, or eight transducers. Two cases are studied for patterning: (1) when all the transducers are excited in phase; (2) when the transducers are excited with a phase delay in the tweezer system. Furthermore, by varying the relative phase of the sinusoidal excitation of the transducer elements, it is possible to translate the position of the acoustic pressure patterns within the operating area of the device. Design and verification of device operation has been carried out by modelling the transducers as linear arrays of cylindrical point sources and super-imposing the patterns using Huygens principle.

Only geometrical configurations that consist of opposing pairs of large transducers are considered. Each pair of transducers produces a near planar standing wave field, and the total field is the sum of the contributions from all the excited pairs. The balanced arrangement of opposing transducers reduces streaming by maximising the ratio of standing waves to traveling waves within the operating area.

Two classes of patterns are of particular interest for particle manipulation: (1) those with translational symmetry, which repeat over the two dimensional plane; (2) those without such symmetry, but allow a single central trap to be produced. The problem of determining what shapes can be used to tile a two-dimensional plane using only two spatial translations is well established in translational geometry and leads to patterns with 17 possible symmetry groups[13] (the wallpaper groups). The main constraint on the available symmetries is the crystallographic restriction that requires that if the lattice covering a two dimensional plane has rotational symmetry for sectors of $2\pi/m$ radians, then $m = 2$, 3, 4, or 6. Such patterns can be achieved acoustically using $N = 2$, 3, 4, or 6 plane waves. An eight sided device is capable of generating patterns using 2, 4, or 6 plane waves, plus a further pattern with $m = 8$, which does not repeat, but does lead to a central trap. The system is shown schematically in Fig. 1(b).

In all cases, if all the incident waves are generated at a regular surface with the same phase then the centre of the system (equidistant from every source) will constitute a pressure amplitude antinode. However, an alternative mode of operation can be produced, where the phases are delayed around the system, in order to give a pattern with a pressure node at the centre. The required phase delays for N transducers are given by

$$\phi_n = \frac{2\pi\upsilon(n-1)}{N}, \tag{1}$$

where $n = 1, 2, \ldots N$ and υ is an integer that determines the phase separation between the transducers.

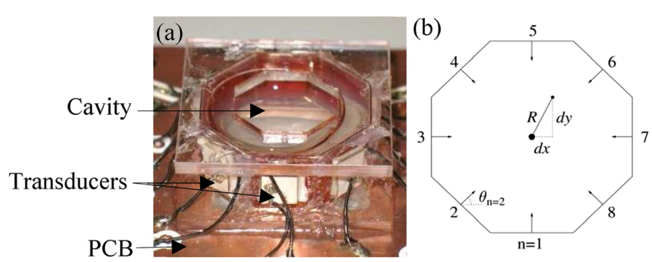

FIG. 1. (a) Photograph of the octagonal tweezers. (b) Diagram showing eight sources of plane waves, labelled n = 1, 2, 3,… N = 8. Arrows indicate direction of propagation of the waves, which are directed at an angle θ_n to the x-axis. The coordinate system used for the translation of the pattern by R is also shown.

It is possible to translate the entire field by applying further phase changes to the excitations. For plane waves, assuming that standing waves arising from reflections within the cavity can be neglected, this delay, represented as a phase angle, is equal to the projection of the translation onto a unit vector perpendicular to the wavefront

$$\phi_n' = -ikR\cos(\theta_n - \theta_R), \tag{2}$$

where k is the wavenumber in the fluid medium and the pattern is to be translated by the vector with magnitude R and angle θ_R. θ_n is the angle between the direction of propagation of the plane wave generated by the nth transducer and the x axis. This phase change can be made in addition to the phase change of Eq. (1) to allow control of both the shape and position of the pattern, i.e., the total phase delay on the nth transducer is $\Phi_n = \phi_n + \phi_n'$.

In practice, reflection within the cavity leads to a deviation from the linear relationship between translation distance, R, the phase delay, ϕ_n', as described by Eq. (2); thus, we would expect to see a deterioration in performance. However, it has been shown before in devices with a considerable reflection coefficient at the transducer that precise translation, using phase control, over several wavelengths can be achieved.[10] In our work we demonstrate smaller translation distances (less than half a wavelength); thus, the relatively high reflection coefficient is tolerable.

A single opposing pair of transducers, e.g., (1, 5) in Fig. 1(b), will result in a pattern with π rotational symmetry ($m = 2$) and translational symmetry in one dimension with a period of λ, and linear nodes, parallel to the transducer faces, at which particles are trapped, separated by $\lambda/2$. Two orthogonally arranged pairs of transducers, e.g., (1, 5) and (3, 7), result in a pattern with $\pi/2$ rotational symmetry and translational symmetry in two perpendicular directions of with a period of $2\lambda/\sqrt{2}$, i.e., a grid pattern with particle traps separated by $\lambda/\sqrt{2}$. With three pairs of transducers, e.g., (1, 5), (4, 8), and (3, 7), a $2/3\pi$ rotational symmetry would be obtained.

In order to generate the desired patterns, a device consisting of eight transducers, with lateral dimensions substantially greater than the wavelength of the generated waves, was fabricated. Eight 5 mm × 5 mm plates of NCE51 Noliac ceramic lead zirconate titanate (PZT) had alumina loaded epoxy matching layer applied. The thickness of the matching layer was optimised using one-dimensional transmission line model to minimise the reflection of the incident waves.[10] The matching layers reduce resonances that would result in unwanted standing waves with nodal positions that were fixed by the geometry thus inhibiting translation of the field by phase variation, as has been demonstrated with both 2 and 4 element devices.[10,14] The transmission line model indicated that even without an absorbing backing layer, manipulation is viable. Addition of an absorbing backing layer would improve the consistency of pressure amplitude (and hence trapping strength) as the field is translated but with increased fabrication difficulty. Matched plates without a backing layer were sufficient for the aims of this work. The matched plates were bonded to a flexible kapton ribbon that was then folded into an octagon.

Synchronisation between channels was achieved using two linked arbitrary waveform generators providing four output channels each (TGA12104, Aim and Thurlby Thandar Instruments, UK) allowing independent control of the amplitude, phase, and frequency of each channel. The signals from the waveform generators were amplified and electronically matched by high speed buffers (BUF634T, Texas Instruments, USA). The system is controlled by a virtual control panel developed in LabVIEW (National Instruments, UK), which allows real time voltage, frequency, and phase control. The interface allows interactive and precise positioning and manipulation of the micro particles.

The device methodology deployed here offers several advantages over previously shown low-element-count approaches using bulk waves,[10,14] including a compact overall device, compatibility with sterile cell culture, simplicity of fabrication, experimental setup and control, and the potential for integration with analytic sensors modules.

Patterning and controlled displacement of microparticles was demonstrated both experimentally and by using a computational model to predict the pressure fields. The wave field generated by one transducer, $g(r)$, was modelled as the sum of several cylindrical point sources, $f(r)$, using Huygen's principle

$$f(r) = Ae^{\frac{-\alpha r}{\lambda}}\cos(\omega t - kr + \Phi), \tag{3}$$

$$g(r) = \sum_{i=1}^{n} f(r_i), \tag{4}$$

where A is the amplitude, α is the damping factor, λ is the wavelength, and Φ is the initial phase. The device boundaries were assumed to be perfectly absorbing.

Patterning and displacement experiments were performed using 10 μm diameter polystyrene microspheres (Polysciences Europe, Germany). The transducers were excited at a frequency of 4.00 MHz with amplitude 8 V_{pp}. At this frequency, the wavelength of the sound waves in water was $\lambda = 375\ \mu$m. Figs. 2 and 3 show the computer simulation results of the

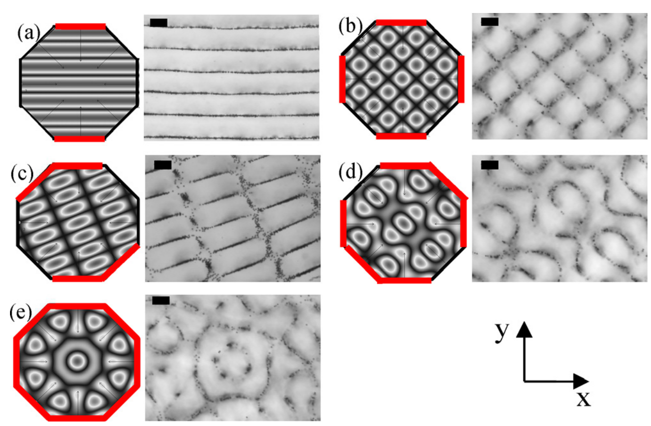

FIG. 2. Computer simulations and experimental observations of the acoustic landscape obtained with (a) two, (b), (c) four, (d) six, and (e) eight transducers when they are excited in phase. For each figure the simulation is on the left, and the experimental result using 10 μm polystyrene beads is on the right. The active transducers are shown in red bold line on the simulation. In the simulation the acoustic potential energy maxima are white, and the acoustic potential energy minima are black (scale bar = 100 μm for the right-hand images).

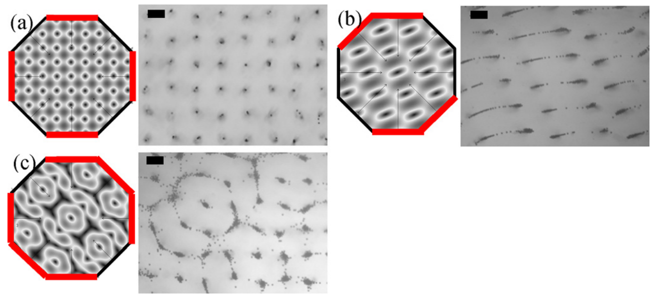

FIG. 3. Computer simulations and experimental observations of the acoustic landscape obtained with (a) two, (b) four, (c) six transducers excited simultaneously with a phase delay. For each figure the simulation is on the left, and the experimental result using 10 μm polystyrene beads is on the right. The active transducers are shown in red bold line on the simulation. In the simulation the acoustic potential energy maxima are white, and the acoustic potential energy minima are black (scale bar = 100 μm for the right-hand images).

acoustic landscape obtained with two, four, six, and eight transducers and the corresponding experimental results. Fig. 2 corresponds to the case when all the excited transducers are stimulated in phase. Fig. 3 corresponds to the case when the transducers are excited at different phases ($\upsilon = 1$).

It can be seen from the computational results in Figs. 2 and 3 that regular standing wave patterns are achieved in the middle of the octagonal cavity at the intersection of the travelling waves. The micro-particles are trapped at the minima of the potential acoustic energy density.[15] From Figs. 2 and 3, it can be seen that the patterning of the trapped particles experimentally follows this behaviour.

For two active transducers, a linear pattern of nodes and antinodes is formed (Fig. 2(a)). The distance d between the nodes is $d = 188\,\mu$m, as expected. When two pairs of transducers are excited (Figs. 2(b) and 3(b)), with an angle between the pairs of $\theta = 90°$, the separation between the lines in the grid pattern are $\Delta x = (\lambda/2)/\sin(\theta/2)$ and $\Delta y = (\lambda/2)/\cos(\theta/2)$; hence, the separation is $\Delta x = \Delta y = \lambda/\sqrt{2} = 265\,\mu$m. When two adjacent pairs of transducers are excited (Fig. 2(c)), a rectangular pattern is obtained. For the case shown in Fig. 2(c), where $\theta = 45°$, $\Delta x = 1.31\lambda = 491\,\mu$m, and $\Delta y = 0.54\lambda = 202\,\mu$m. Exciting six transducers (Figs. 2(d) and 3(c)) with transducers are arranged with two pairs (3, 7) and (1, 5) arranged at 45° either side of the central pair (2, 6) gives more complicated patterns. The pattern is periodic perpendicular to the common axis of the central pair and has a period of $\lambda/\sqrt{2}$. For $\upsilon = 1$, the nodes are therefore separated by $d = \lambda/\sqrt{2}$. The simulation and experiment are in good agreement in all cases.

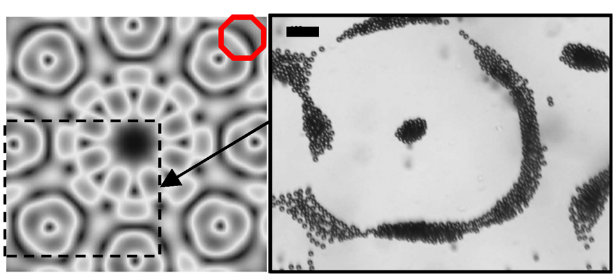

FIG. 4. Computer simulation (left) and experimental micrograph (right) when 8 transducers are simultaneously excited with $\upsilon = 3$ (scale bar = 100 μm for the right-hand image).

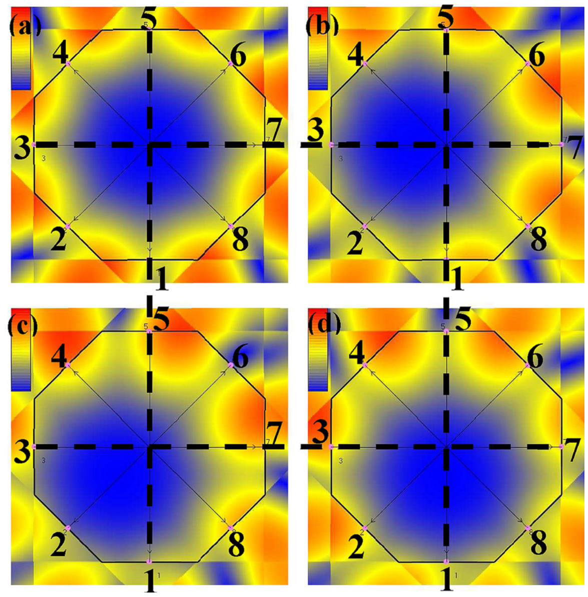

FIG. 5. Displacement of the centre trap by adjusting the phase of eight transducers (a) coordinate position (0, 0), (b) position ($-50\,\mu$m, 0), (c) position ($-50\,\mu$m, $-50\,\mu$m), (d) position (0, $-50\,\mu$m).

When exciting all eight transducers in phase (Fig. 2(e)), the nodes form a circular trap, with an acoustic pressure maximum at the centre. By changing the phase of the eight transducers in accordance with Eq. (1) with $\upsilon = 1$, 2, 3, or 4, a pressure minimum at the centre is obtained that is suitable for tweezing. The size of the acoustic minima is controlled by increasing υ. Fig. 4 shows a computer simulation and experimental micrograph when eight transducers are simultaneously excited when $\upsilon = 3$. It can be seen that a good match between simulation and experimental data was achieved.

In order to demonstrate a tweezing action it is required that we translate the position of the central node. The appropriate phases to translate the trap were determined using Eq. (2). Fig. 5 shows a simulation of central region of the main trap in which it is shown that different translations of the central node, by 50 μm along the x- and y-axis, are possible. Fig. 6 shows the same translation can be obtained experimentally when trapping and manipulating polystyrene beads.

In conclusion, we have presented an octagonal sonotweezer that can provide multiple patterning shapes in one device by changing the number, arrangement, and applied-signal phase of pairs of transducers that are simultaneously excited. A computer interface that was developed for the tweezers system enabled different patterns of micro particles to be achieved by combining different pairs of transducers and by delaying the phase of the transducer excitation around

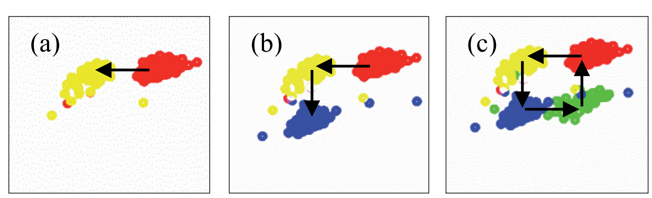

FIG. 6. Overlay of micrographs taken at different relative phase shifts of the 8 transducers demonstrating the manipulation of the main trap (a) from coordinate (0, 0) to ($-50\,\mu$m, 0), (b) from ($-50\,\mu$m, 0) to ($-50\,\mu$m, $-50\,\mu$m), and (c) from ($-50\,\mu$m, 50 μm) to (0, 0).

the tweezers system. The octagonal sonotweezer has demonstrated precise positioning and manipulation control of micro particles at different location on a surface and allows higher spatial resolution compared to previous devices. Excellent agreement between computer simulation and experimental results has been demonstrated. Acoustic tweezing devices with large numbers of transducers are highly desirable for the manipulation of micrometre scale materials, including cells, since a high degree of precision and flexibility is possible using only electronic control. The octagonal device described in this letter is compatible with sterile cell culture thus is suitable for biomedical applications. The simplicity in experimental setup and compact device dimensions enables use in incubators or microscopes. The octagon device has a relatively large working area (2 cm) allowing versatility and the introduction of materials such as treated cover slips for use in bioassays or tissue engineering applications. Future work will involve investigating complex cell patterning for tissue engineering applications.

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[1]F. Christopher, J. C. Shu, and N. B. Sangeeta, Nat. Methods **2**, 119–125 (2005).

[2]M. M. Stevens, M. Mayer, D. G. Anderson, D. B. Weibel, G. M. Whitesides, and R. Langer, Biomaterials **26**, 7636–7641 (2005).

[3]M. Saito, T. Daian, K. Hayashi, and S. Izumida, J. Appl. Phys. **83**, 3490–3494 (1998).

[4]J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, A. Lawit, and T. J. Huang, Lab Chip **9**, 2890–2895 (2009).

[5]T. Laurell, F. Petersson, and A. Nilsson, Chem. Soc. Rev. **36**, 492–506 (2007).

[6]M. C. Jo and R. Guldiken, Sens. Actuators, A **187**, 22–28 (2012).

[7]J. Hu, C. Tay, Y. Cai, and J. Du, Appl. Phys. Lett. **87**, 094104 (2005).

[8]C. D. Wood, J. E. Cunningham, R. O'Rorke, C. Walti, E. H. Linfield, A. G. Davies, and S. D. Evans, Appl. Phys. Lett. **94**, 054101 (2009).

[9]L. Meng, F. Y. Cai, J. J. Chen, L. L. Niu, Y. M. Li, J. R. Wu, and H. R. Zheng, Appl. Phys. Lett. **100**, 173701 (2012).

[10]C. R. P. Courtney, C. K. Ong, B. W. Drinkwater, A. L. Bernassau, P. D. Wilcox, and D. R. S. Cumming, Proc. R. Soc. London, Ser. A **468**, 337–360 (2012).

[11]A. L. Bernassau, O. Chun-Kiat, M. Yong, P. G. A. Macpherson, C. R. P. Courtney, M. Riehle, B. W. Drinkwater, and D. R. S. Cumming, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **58**, 2132–2138 (2011).

[12]A. L. Bernassau, F. Gesellchen, P. G. A. MacPherson, M. Riehle, and D. R. S. Cumming, Biomed. Microdevices **14**(3), 559–564 (2012).

[13]G. E. Martin, *Transformation Geometry: An Introduction to Symmetry* (Springer-Verlag, New York, 1982), pp. 88–116.

[14]C. R. P. Courtney, C. K. Ong, B. W. Drinkwater, P. D. Wilcox, C. Demore, S. Cochran, P. Glynne-Jones, and M. Hill, J. Acoust. Soc. Am. **128**, EL195–EL199 (2010).

[15]A. L. Bernassau and D. R. S. Cumming, in IEEE International Ultrasonics Symposium, 18-21 October 2011, pp. 1537–1540.